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Review

Precooling and Cold Storage Methods for Fruits and Vegetables in Sub-Saharan Africa—A Review

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Abstract: Fruits and vegetables, known for their large nutrient potential, are more susceptible to high postharvest loss than other crops. Factors such as perishability, poor post-production handling and storage and processing infrastructures, increase the magnitude of food losses. The postharvest loss of fruits and vegetables in Sub-Saharan Africa ranges from 30% to 50%. One key strategy to overcome such losses is through cold chain integration in value chains. However, most developing countries currently lack the basic infrastructure and management skills needed to support the development of integrated cold chains, particularly in rural areas, where up to 60% of overall food losses occur on the farm and in 'first-mile' distribution. Storage of highly perishable produce in a controlled environment with respect to temperature and relative humidity leads to quality and quantity preservation. This contributes to increases in food and nutrition security, household incomes and environmental protection. This review addresses the need for adopting and strengthening measures for the precooling and cold storage of fruits and vegetables to improve their value chains. A range of precooling and cold storage methods, their suitability, energy demands and the constraints on storage and distribution are discussed and recommendations are made on how to improve their accessibility for small-scale farmers in rural communities.

Keywords: cold chain; fruits and vegetables; postharvest loss; food and nutrition security

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1. Introduction

The world's population is projected to increase to over 10 billion by the year 2050, which will require a 70% increase in food production [1,2]. However, increasing food production should go hand in hand with reduction of food losses and waste [3]. There is substantial food loss along the supply chain in Africa, especially in Sub-Saharan Africa (SSA) [4], as a result of inefficient supply chains and storage infrastructures within the agricultural sector [5,6]. Moreover, SSA has the highest prevalence of undernourishment in the world. The number of undernourished people in SSA rose from 172 to 264 million between 2010 and 2020 [7]. Although several technical, financial and policy-making efforts in private and public sectors in different SSA countries are helping to combat food losses [8], there is still a lot of work to be done to achieve zero hunger.

Large food losses are a threat to food and nutrition security, resources (land, water, energy and inputs such as fertilizers, pesticides and capital), climate and the incomes and livelihoods of millions of people, particularly in SSA [6,9,10]. The lack of knowledge of postharvest handling, the low level of technology, climate change, and poor investment in food value chains are amongst the drivers of postharvest food loss [6,11]. Although food losses happen at every stage of the supply chain, in the SSA region, more than 38% of food losses occur at production, postharvest handling and processing levels [6,12]. However, food losses during retail and in consumers' homes are also significant [13]. Reducing postharvest losses in SSA is a key pathway to food and nutrition security in order to achieve zero hunger by 2030 [3]. The benefits of reducing postharvest losses include: increase in food availability and supply that may ultimately increase food security; increase in household incomes through extra sales of food; and reduced pressure on climate, energy, water and land resources through the reduction of greenhouse gas emissions (mostly carbon dioxide and methane) and efficient utilization of limited natural resources [6,12,14,15].

Fruits and vegetables represent the highest magnitude of postharvest losses due to their perishable nature and the poor post-production infrastructure for adequate handling of these crops [3,11]. The total loss accounts for about one-third of all harvested fruits and vegetables worldwide [16]. It is estimated that, along the entire value chain of fruits and vegetables in SSA, about 16–52% of produce is lost [6,17]. In Tanzania, up to 50% of fruits and vegetables are lost every year as a result of poor postharvest handling, storage and processing [18]. Hence, appropriate postharvest technologies need to be employed to preserve the quality and quantity of fresh fruits and vegetables along the value chain.

Cold chain systems, such as cold storages, are crucial to minimizing postharvest losses of fresh fruits and vegetables [19]. However, cold storage alone cannot prevent crop losses, but should be considered as one component that needs to be integrated into a cold chain network from the point of harvest to the point of purchase by the consumer [20]. Cold chains are still in their infancy in developing countries due to the lack of basic infrastructure and management skills needed to support the development of integrated cold chain systems. In rural areas in particular, where the 'first mile' of most food value chains is located and within which up to 60% of overall food losses occur, functional cold storages are frequently absent [21]. Through improving access to refrigeration, the spoilage of up to 475 million tonnes of fresh foods could be prevented. Theoretically, this amount could feed 950 million people a year [22]. In addition, improving other aspects of supply chain management, such as market infrastructures, will help improve the effectiveness of cold storage and distribution [23].

The present review discusses the potential of cold storage technologies in reducing postharvest losses of fruits and vegetables. The review presents a detailed overview of available precooling and cold storage methods, their management and energy needs, the status of cold storage in Tanzania and demand for the cooling of fresh fruits and vegetables. It also provides recommendations for sustainable integration of cold storage and distribution in Sub-Saharan Africa.

2. Cooling and Cold Storage of Fresh Fruits and Vegetables

A cold chain for perishable foods can be defined as the uninterrupted handling of the product within a low-temperature surrounding during the postharvest steps of the value chain [24]. After harvest, a food cold chain pathway includes precooling, bulk storage, distribution, retail cooling and household refrigeration before consumption. Although a cold chain does not necessarily have to include all of the aforementioned steps, it must involve at least one of these steps [24]. This section provides an overview of precooling and bulk storage methods for fresh fruits and vegetables.

Bulk cold storage refers to the storage of (large) quantities of produce after production and initial post-production handling. Bulk cooling may take place on farms, at production facilities, at collection/grading centers or at processing facilities. Precooling of products prior to bulk cooling is necessary in order to achieve desired temperature reductions faster than direct integration into bulk storage [20]. Cooling and cold storage require enough starting capital and running costs and reliable electricity supply. These preconditions are often not available to farmers in developing countries. Hence, small-scale farmers have no access to unbroken cold chains and the use of sustainable cold storage facilities [25].

In general, improving cold storage in food value chains provides significant development benefits, such as expanding access to suitable infrastructures and strengthening local management capacities. It also offers environmental protection by reducing waste and carbon emissions, providing efficient use of natural resources and accelerating economic growth through energy and cost savings and increased incomes to rural farmers [20,25,26].

2.1. Precooling Methods for Fruits and Vegetables

Elansari [27] defined precooling as "the removal of field heat from freshly harvested perishable produce in order to slow down metabolism and lower deterioration prior to transport or storage". Field heat means the difference in temperature between the temperature of harvested produce and the optimal storage temperature of that produce. In addition, field heat should be removed as fast as possible since, for most fresh produce, an hour's delay at field temperature conditions of 35 °C will lower shelf life to about a day even at optimal storage conditions [28]. Soon after harvest, fresh produce looses more water (through transpiration and respiration), probably due to stress at harvest. Additionally, water loss results in decreased product weight and freshness, while in extreme cases all of the produce becomes unsaleable. Therefore, rapid cooling of fresh produce soon after harvest reduces the rates of respiration and transpiration, ethylene production and microbial growth thereby enhancing its freshness and nutritional value and preventing or delaying chilling injury [27,29]. Furthermore, precooling increases the daily intake of produce into a cold storage facility, which should be less than 10% of its cooling capacity if produce is not precooled, reducing the thermal load of cold storage, since optimum storage temperature is reached more quickly [28]. Studies have shown that the postharvest losses of commercial fruits and vegetables are about 25–30% without precooling and only 5–10% with precooling [30].

The choice of a particular precooling method for fruits and vegetables depends on multiple factors, such as the characteristics of the produce (including chilling sensitivity, geometry and thermal properties), the amount of produce to be cooled, air temperature, airflow rate, relative humidity, packing configuration and stacking arrangement of the produce, energy efficiency of the method, the availability of skilled labor and the economic viability (capital and running costs) of the precooling method [27,28,31,32].

Several studies in the literature on precooling methods for fresh fruits and vegetables are available [27,29,31,33,34]. Precooling methods, such as refrigerated room cooling, passive evaporative cooling, forced-air cooling, water cooling and ice cooling, along with their impacts, are compared in Table 1.

Table 1. Comparison of precooling methods and their effects on horticultural produce [27,31].

Methods	Passive Evaporative Room Cooling (Use of Water-Soaked Media)	Refrigerated Room Cooling (Cold Air Is Circulated around Containers)	Forced-Air Cooling (Cold Air Is Forced through Containers)	Water Cooling (Cold Water Is Used for Fast Cooling)	Ice Cooling
Example of available systems	Clay-in-clay passively cooled rooms; zero-energy cooling chambers (sand and bricks); charcoal-filled walls of non-refrigerated rooms	Traditional cold rooms (pre-fabricated/self-built); retrofitted refrigerated container trailers; USDA Porta-cooler (small trailer-mounted pre-cooler)	Portable forced-air pre-cooler; Cool & Ship (insulated precooling box with A/C unit); TORNADO mobile forced pre-cooler	Mobile coolers; immersion-type conveyor coolers; shower-type batch coolers	Package ice—crushed or slurry ice
Typical cooling time (h)	40–100	20–100	1–10	0.1–1.0	0.1–0.3
Produce moisture loss (%)	No data	0.1–2.0	0.1–2.0	0–0.5	No data
Water contact with produce	No	No	No	Yes	Yes
Potential for decay contamination	Low	Low	Low	High	Low
Capital cost	Low	Low to medium	Low	Low	High
Energy efficiency	High	Low	Low	High	Low
Limitations and concerns	Applicability and effectiveness limited by climatic factors; severely restricted temperature range	Produce should not be harvested while hot to reduce water loss and/or microbial infections	Effectiveness is limited by air flow configuration used, which may increase cost	Recirculated water must be clean to avoid buildup of decay organisms	Ice melting causes physical hazards during operations; need for moisture-proof packages

2.2. Bulk Cooling Systems for Storage of Fruits and Vegetables

Common cooling methods for bulk storage are vapor-compression systems, sorption systems and evaporative cooling systems. These systems are compared in Table 2. The technologies differ significantly with regard to a range of characteristics, such as temperature and relative humidity range, as well as energy and refrigerant use. The choice of cold storage system to be installed and site selection depends on many factors that include [20,35]: the level of temperature and relative humidity required; the location chosen should be easily accessible and close to produce collection points; uninterrupted supplies of electricity and water the availability of capital and skilled labor; and the economic value generated through cold storage to justify investment and running costs. Moreover, the selected technology needs to be sustainable and environmentally friendly, with zero or low greenhouse gas emissions [26]. Where feasible, the use of off-grid electricity, zero or renewable energy, and natural refrigerants should be highly encouraged. Accordingly, solar photovoltaic systems, wind power and biomass energy are gaining traction in the fast-growing renewable energy sector in Africa [36]. For instance, with 69% of the total final energy consumption in 2017 being from renewable energy sources, Sub-Saharan Africa showed the highest share of this sector. Hence, sustainable energy can be effectively harnessed to power off-grid cold storage facilities.

Table 2. Comparison of cold storage methods and designs with key operational characteristics [20].

Methods	Common Systems (*Design*)	Energy Requirement	Temperature Provided	Refrigerant
Evaporative coolers	Zero-Energy Cooling Chamber (*Walk-in cold room/chest-type cooler*)	No energy input required; optional use of low-voltage electric pumps and fans	Vary widely depending on outside temperature and humidity; no less than approx. 15 °C	Water (frequent refills required)
	USDA-Portacooler Evaporative Forced-Air (*Refrigerated trailer*)	12/24V DC deep cycle battery		
	Charcoal cooler (*Walk-in cold room/chest-type cooler*)	No energy input required; use of electric pumps/fans is optional		
Sorption coolers	Cooler (*Solar adsorption cooling*)	Thermal energy 520 kWh/a/~60 W (80 °C)	4 °C to 8 °C	Distilled water
	Solar Polar (*Adsorption cooling modules*)	Solar thermal energy (evacuated tube); thermal energy storage	Not specified	Ammonia–water
Vapor compression coolers	DanSolar Cold Storage Chamber (*Walk-in cold room*)	Off-grid standalone solar PV refrigeration	−10 °C to 10 °C	Not specified
	Steca PF 166/PF 240 (*Chest-type cooler*)	12/24 V DC designed for off-grid solar PV operation	2 to 12 °C (refrigerator) or −20 to −10 °C (freezer)	Halogenated (R134a)
	CoolBot (*Walk-in cold room/refrigerated trailer)*	110 V AC	2 °C and above	Halogenated or natural refrigerant

2.2.1. Vapor-Compression Cooling System

Vapor-compression cooling is an electric-driven system which relies on phase changes of refrigerant fluid [20,37]. During operation, a circulating liquid refrigerant (halogenated or natural refrigerants) is exposed to different pressures successively. When subjected to low pressure surroundings, the liquid refrigerant evaporates while it absorbs and removes heat from its surroundings to provide a cooling effect. Subsequently, the gaseous refrigerant is first compressed and then condensed returning to its liquid state, while rejecting the heat previously absorbed to the environment.

This cooling method provides a full temperature range and a relative humidity of 80% to 90% which makes it suitable for chilling even high-value produce. Economically, this kind of cooling system has lower initial investment costs but may have high running costs depending on whether the cold room is pre-fabricated or owner built, new or used, and high maintenance costs [31]. This system has a comparatively high Coefficient of Performance (COP), which is the ratio between refrigerating capacity and power consumed. A shortcoming of this method has been the use of halogenated refrigerants, which, though widely available and relatively cheap, are not environmentally friendly. Natural alternatives, such as hydrocarbons, carbon dioxide and anhydrous ammonia, are now commercially available as alternatives but they are still relatively expensive in developing countries [20].

2.2.2. Sorption Cooling System

A sorption cooling system runs on thermal energy and relies on physicochemical attraction between a natural refrigerant and an adsorbent or absorbent [20]. Ammonia–water or lithium bromide–water combinations are mostly used in absorption systems, while silica gel–water or zeolite–water working pairs are mostly used in adsorption systems. To create a cooling effect, the refrigerant is subjected to a low-pressure surrounding in order to evaporate at ambient temperature while absorbing heat from its surrounding. Subsequently, the gaseous refrigerant is absorbed or adsorbed by the absorbent or adsorbent material. As a result, the pressure in the evaporator is reduced allowing more refrigerant to evaporate. Thermal energy is then used to evaporate the refrigerant from the adsorbent or absorbent and restore the original conditions.

Similar to vapor-compression systems, sorption cooling can provide a full temperature range and low/medium relative humidity. This makes it suitable for chilling sensitive and even high-value produce. Sorption cooling systems require higher capital costs and very low operating costs due to their flexible use of low-grade thermal energy sources (such as solar and industrial waste heat) and low maintenance requirements. In addition, sorption systems have lower COP compared to vapor-compression systems [20].

2.2.3. Evaporative Cooling System

An evaporative cooling system utilizes the cooling effect resulting from the evaporation of water [20,38]. Water is applied to a porous surface (e.g., sand or charcoal). As temperatures increase, it begins to evaporate. As water undergoes a phase change from liquid to gas, it absorbs energy in the form of heat from the surrounding air, thus cooling it. This simple cooling method only requires water as a coolant, running freely over a porous surface, and, since the process is driven by heat from the surrounding environment, requires no additional energy [35]. However, the cooling process if it relies on natural flow of air is slow and can be speeded up by using fan-assisted air flow systems.

Evaporative cooling systems are comparatively cheap due to the fact that they require very little or no energy input, can be constructed using locally available materials (e.g., bricks, charcoal and sand) and water as a coolant, and thus can be suitable for low-value produce [17,31,35,38]. However, this method provides limited temperature control due to its inherent dependence on local climatic conditions [39]. In most cases, temperatures above 15 °C and very high relative humidity are achieved. Hence, evaporative systems are mostly suitable for non-chilling fruit and vegetables, especially tropical/sub-tropical crops, such as tomatoes, mangoes, bananas, sapotas, plums, grapes, capsicums, cluster beans, peas, radishes, peaches, carrots, cucumbers, beats, ladies fingers, green peppers, cauliflowers and leafy vegetables [35]. As the availability of water is a critical factor in the operation of evaporative cooling systems, a continuous supply of reasonably sanitized and soft (i.e., no or low levels of calcium or magnesium) water in sufficient quantity, along with suitable water pumping technology and water storage reservoirs, are required [20].

3. Cold Storage Management

Prior to precooling and bulk storage of fruit and vegetables, appropriate harvesting and handling of fresh produce, taking into account maturity and ripeness levels and proper harvesting time (during periods of low temperatures or sunlight intensities), along with sorting and grading and adequate packaging, should be considered to avoid loss of quality through mechanical, chilling and freezing injuries and microbial growth, to extend shelf life during cold storage [29,33–35,40,41].

To improve the shelf life and quality of fresh fruits and vegetables, cold storage should be managed properly with regard to temperature, relative humidity levels, air flow, space between storage containers, mixing of compatible produce (e.g., according to temperature demand, odor production and ethylene sensitivity), as well as the management of product in- and outflow, which should follow the 'First In, First Out' principle [28,33,41,42]. In fact, the principle is to store each crop separately and the climacteric products at similar maturity stages. Since this is not always feasible, compatible crops can be stored together. For instance, with respect to odor transfers, apples and pears should be separated from celery, cabbage, carrots and onions. Additionally, storing celery with onions or carrots and citrus fruits with strongly scented vegetables should be avoided. Ethylene-producing crops, such as bananas, apples, avocadoes, peaches, plums and tomatoes, should be stored separately from ethylene-sensitive crops, such as carrots, lettuce, cucumbers and potatoes. Further to this, cold storage facilities should be cooled to the storage temperature required for the specific products before produce is stored.

Cold storages could be accompanied by modified-atmosphere technologies, such as Controlled Atmosphere (CA) storage and Modified Atmosphere Packaging (MAP), to further improve the effect of cooling on fresh fruits and vegetables. While CA storage replaces the traditional refrigerated storage rooms, MAP focuses on the environments of products within packaging. Nevertheless, both technologies consider the manipulation of the level of gases, such as oxygen (O_2), carbon dioxide (CO_2) and nitrogen (N_2), as a means to control fresh produce quality and storability through suppression of respiration (via high CO_2 and low O_2 conditions), inhibition of ethylene action (via high CO_2, low O_2), inhibition of decay (via high CO_2) and inhibition of browning for fresh-cut produce (via low O_2) [43,44]. In addition, the amount of water loss of fresh produce is reduced considerably, particularly in MAP. The application of CA storage is more intensive and active, as it relies on costly techniques, including the use of CO_2 scrubbing methods to control CO_2 levels, improved technologies for generating low O_2 atmospheres and improved sense-and-respond systems for atmosphere control. On the other hand, MAP is more passive and hence cost-effective in low-income SSA countries. MAP can be further improved through the use of biodegradable plastics, sensors and the incorporation of bioactive compounds, such as absorbers of CO_2, O_2 and water vapor.

Edible coatings, such as some lipids, proteins, polysaccharides or mixed biopolymers, could be applied on fresh fruits and vegetables during cold storage to maintain quality (including texture, color and nutritional value) and extend shelf life [45,46]. Edible films form a thin semi-permeable layer when applied over the surface of fresh produce to provide a modified atmosphere during storage. As a result, gas transfer, water loss, color change and aroma loss are reduced. In addition, some edible films are carriers of antimicrobial and antioxidant agents and hence help to control microbial growth and biochemical activities, such as respiration and transpiration. Therefore, where applicable, the combination of optimal storage temperatures, relative humidity levels, atmospheric gases and edible coatings could improve the effectiveness of cooling techniques for fresh produce.

The operation and maintenance of a cold storage facilities is necessary to ensure that the purpose of cooling is achieved. Due to the costly and energy-intensive nature of cold storage facilities [20], the door to the cold storage room should be opened as few times as possible, particularly in the early morning or evening hours. In addition, the usage of lighting and fans should be kept to a minimum [29]. A logbook should be used to keep all information on incoming produce up-to-date, such as harvest date, precooling method used, arrival and storage time, quality, quantity, storage conditions, energy consumption, and location within the cold storage facility [28]. Moreover, good hygienic practices inside the cold storage facility, such as personnel hygiene, facility cleanliness, maintained with hypochlorite solution and ozone generators, and regular ventilation to reduce concentrations of carbon dioxide, ethylene and odors, should be taken into consideration [47].

Cold storage control systems can also be integrated with modern intelligent control methods, such as frequency-controlled compression technology, Programmable Logic Controller (PLC) technology, fuzzy control, in combination with Internet of Things, to optimize the control of cold storage for low-energy consumption, cost saving and low environmental impact [48].

4. Status of Cold Storage and Its Potential for Fruits and Vegetables in Tanzania

The growth of the horticulture industry in Tanzania has grown between 9–13% in the last seven years. This represents the fastest growth subsector of the agricultural sector in Tanzania [49]. According to the Tanzania Horticultural Association (TAHA), the horticulture sub-sector contributed 38% (USD 296 million) of the foreign income of the agricultural sector in 2019, which had a total contribution of USD 779 million [18]. Tanzania's horticultural industry is dominated by smallholder farmers (about 65–70% being women), with export of fruits and vegetables dependent on farmers with landholdings of less than 2 hectares representing 70% of this [50]. In addition, fruit and vegetable production in the horticultural subsector accounts for the largest percentage of horticulture exports [51]. There are diversified varieties of fruits and vegetables cultivated in Tanzania, such as chives, baby corn, beetroots, beans, cabbages, carrots, cauliflowers, eggplants, onions, okra, green/snow peas, potatoes, spinach, tomatoes, pineapples, bananas, avocadoes, blackberries, mangoes, apples [18] and cashew apples [52].

In Tanzania's horticultural sector, food losses at domestic market and export market are estimated at 40% and less than 10%, respectively. Furthermore, about 25% of the total amount of vegetables produced at each harvest are is wasted due to the unavailability of effective postharvest facilities [49]. Highly perishable fruits, such as cashew apples, are hardly utilized, even in production areas, due to the absence of affordable cold storage facilities, among other factors [52]. Even though cold storage facilities can reduce postharvest losses the available cold storage rooms are expensive to use and cannot be afforded by small-scale farmers. There are also inadequate numbers of low cost off-grid cooling methods for fresh produce, such as Charcoal Cooling Rooms (Figure 1) and Zero-Energy Cooling Chambers (ZECCs) (Figure 2). Passive evaporative coolers have some shortcomings, such as shorter storage times, limited size of the cooling chambers, difficulty of temperature control and management, which make them suitable only for precooling purposes rather than bulk storage. Therefore, further sustainable precooling and bulk storage methods, such as those addressed in this paper, could be adopted. In addition, there is a need to improve capacity-building (e.g., by establishing a center of excellence for sustainable cooling and cold chain) and market infrastructures, such as good road conditions in potential farming areas, in order to increase the availability of fresh fruits and vegetables as well as avoid bruising to fresh produce, hence increasing farmers' incomes, food and nutrition security and the country's economy.

Figure 1. Charcoal Cooling Room for storage of fresh fruits and vegetables in Tanzania.

Figure 2. Zero-Energy Cooling Chamber for storage of fresh fruits and vegetables in Tanzania [53].

As a comparative example, Nigeria is also facing large losses of fresh fruits and vegetables due to lack of adequate cold storage facilities. However, in 2016 the country adopted a social enterprise called ColdHubs [54,55]; these are walk-in, modular, solar-powered cold rooms (Figure 3) which provide uninterrupted storage of fresh produce at farms and marketplaces. These units can extend the shelf life of fresh produce from 2 to 21 days and also provide employment opportunities for women (two women per ColdHub unit being required) (Figure 4). During operation, customers pay nearly USD 0.5 per crate per day of cold storage. It has been reported that nearly 5800 tonnes of fruits and vegetables had been saved from spoilage 2 years after operation, and more than 300 farmers and traders have almost doubled their monthly incomes. Therefore, this approach could be adopted by other Sub-Saharan African countries, including Tanzania, to reduce postharvest losses of fresh fruits and vegetables, increase food and nutrition security, and improve farmer's and trader's livelihoods.

Figure 3. ColdHubs: a walk-in, modular, solar-powered unit for storing fresh produce in Nigeria [55].

Figure 4. Workers fill plastic bins with fresh produce prior to ColdHubs refrigeration in Nigeria [55].

5. General Recommendations for Adopting and Strengthening Cold Storage for Fresh Fruits and Vegetables

1. Improving supply chain management, including market infrastructures, with good road conditions and good supplies of electricity. Investing in off-grid zero or renewable green energy sources, notably wind and solar energy, should be encouraged.
2. Operators and processing staff should be sufficiently trained to safely and effectively operate and maintain cold chain equipment to avoid unnecessary food and energy losses. However, to fully exploit the benefits of cold storage, other stakeholders, such as smallholder farmers, transport companies, traders/distributors, processors, end-consumers, policy makers, financial institutions and researchers, should be trained on their fields of activity.
3. Fruits and vegetables should be graded and sorted before being placed in cold storage. Only top-quality-graded goods should be stored, as they represent a high return on investment after selling.
4. Reducing the number of middlemen involved in food value chains in developing countries can significantly facilitate the viability of introducing and maintaining cold chains. The fragmentation of the value chain, as a result of the large number of stakeholders, constitutes a hindrance towards the development and financing of necessary cold chain infrastructures, as well as effective cold chain management.
5. Adhering to the defined storage capacities is essential for cold storage to be effective. Leaving enough space between stacked crates of produce is essential to allow for good circulation of chilled air for effective cooling of the produce.

6. Fruits and Vegetables: Their Benefits and Demand for Cooling

Fruits and vegetables are widely recognized for their richness in nutrients and bioactive compounds, which play a vital role in human health and well-being. They contain a wide range of nutrients and phytochemicals, such as sugars, vitamins (A, C, E, folate), minerals (phosphorous, potassium, iron, magnesium), essential amino acids, bioactive compounds (polyphenols, carotenoids) and fibers [56,57]. Notably, a high dietary intake of fruits and vegetables could prevent or reduce the risk of developing chronic diseases, such as heart disease, diabetes and cancer [56]. Among other factors, most chronic diseases are caused by the accumulation of free radicals (hydroxyls, peroxyls, nitric oxide) in the body; hence, bioactive compounds act as antioxidants to suppress free radical activity via several mechanisms [58,59]. In addition, fruits and vegetables are essential for maintaining gut microbial flora, which in turn has a profound positive impact on intestinal health and well-being of the host [60]. Adhering to these benefits, it is crucial to reduce postharvest loss of fruits and vegetables to improve food and nutrition security around the world.

Among agricultural products, fruits and vegetables are characterized as highly perishable crops. Perishability varies among horticultural products (Table 3) and is largely influenced by crop water content, softness of tissues and metabolic activity [20]. Fresh crops are live products and contain more field heat and are hence prone to biological deterioration caused by respiration, ethylene production, mechanical injuries, water stress, physiological disorders and pathological breakdown [27]. Deterioration leads to decay, loss in nutritive value, and changes in color, texture and flavor. Thus, field heat should be properly and rapidly removed to preserve the quality of fresh fruits and vegetables. As stated by Elansari [27], an hour's delay in the precooling of highly perishable produce reduces product shelf life by one day. Moreover, exposure to high temperatures for as little as one hour can reduce shelf life by a full day [61]. Food deterioration may increase twice or thrice with every 10 °C increase in temperature. In other words, the reduction of storage temperatures by 10 °C will double the shelf life of horticultural crops [62], as presented in Table 4. Therefore, food deterioration can be addressed by controlling temperature, relative humidity and atmospheric composition (levels of oxygen, carbon dioxide and ethylene), and the sanitation of storage facilities [16,20,42].

Table 3. Relative perishability and shelf life of fresh fruits and vegetables [38,63].

Relative Perishability	Potential Shelf Life (Weeks)	Fresh Fruits/Vegetables
Very high	Less than 2	Apricot, blackberry, blueberry, cherry, fig, raspberry, strawberry; asparagus, bean sprouts, broccoli, cauliflower, green onion, leaf lettuce, mushroom, muskmelon, pea, spinach, sweet corn, tomato (ripe)
High	2–4	Avocado, banana, grape (without SO_2 treatment), guava, loquat, mandarin, mango, melon (honeydew, crenshaw, Persian), nectarine, papaya, peach, plum; artichoke, green beans, Brussels sprouts, cabbage, celery, eggplant, head lettuce, okra, pepper, summer squash, tomato (partially ripe)
Moderate	4–8	Apple and pear (some cultivars), grape (SO_2-treated), orange, grapefruit, lime, kiwifruit, persimmon, pomegranate; table beet, carrot, radish, potato (immature)
Low	8–16	Apple and pear (some cultivars), lemon; potato (mature), dry onion, garlic, pumpkin, winter squash, sweet potato, taro, yam

Table 4. Effect of temperature control on shelf life of fresh fruits and vegetables [29].

Fresh Commodity	Shelf Life at Optimal Temperature	Shelf Life at 35 °C (Ambient Temperature)	Shelf Life at 25 °C	Shelf Life at 15 °C
Cabbage	6 months at 0 °C	2 weeks	4 weeks	8 weeks
Carrot	6 months at 0 °C	2 weeks	4 weeks	8 weeks
Tomato	14 days at 15 °C	3 days	6 days	14 days
Pepper	20 days at 12 °C	3 days	7 days	15 days
Spinach	14 days at 0 °C	1 day	2 days	5 days

Temperature control in the cold storage of fresh crops is of paramount importance. Temperatures either above or below the optimal range can accelerate deterioration as a result of freezing or chilling injury [41]. Since fresh crops have high water contents in their tissues, the freezing point of their tissues is relatively high (ranging from −3 °C to −0.5 °C) and disruption caused by freezing leads to immediate collapse of tissues and total loss of cellular integrity. Chilling injury of fresh produce (particularly of tropical and subtropical origin) occurs after storage at low temperatures that are well above their freezing points but below a critical temperature termed the chilling threshold temperature or the lowest safe temperature, as presented in Table 5. Symptoms of chilling injury include surface and internal discoloration, water soaking, development of off-flavors, uneven ripening and increased susceptibility to pathogen attack [41].

Table 5. Classification of chilling-sensitive fruits and vegetables according to their lowest safe temperatures for transport and storage [41].

Lowest Safe Temperature (°C)	Fresh Fruits/Vegetables
3	Asparagus, cranberry, jujube
4	Cantaloupe, potato, certain apple cultivars (such as Mcintosh and Yellow Newton), certain avocado cultivars (such as Booth and Lula), lychee, tamarillo
5	Cactus pear, cowpeas, guava, longan, durian, feijoa, pepino, kumquat, orange, mandarin, lima bean
7	Chayote, okra, snap bean, pepper, olive, pomegranate, certain avocado cultivars (such as Fuerte and Hass), pineapple
10	Carambola, cucumber, plantain, squash (soft rind), passion fruit, papaya, lime, melons (casaba, crenshaw, honeydew, Persian), eggplant, grapefruit, mango (ripe), tomato (ripe), taro, watermelon
13	Banana, jackfruit, mature–green mango and tomato, lemon, sapotes, mangosteen, breadfruit, cherimoya, pumpkin, hard-rind squash, yam, sweet potato, ginger

The optimal storage conditions, as presented in Table 6, vary widely among fruits and vegetables. Most fruit and vegetables require storage temperatures in the range of −2 °C to 2 °C and approximately 5–15 °C for chill-sensitive crops [63,64]. The University of California at Davis [65] stated that crucifers, leafy vegetables and temperate fruits require temperatures and relative humidity levels in the ranges of 0–2 °C and 90–98%, respectively, while many fruit-type vegetables, citrus and subtropical fruits require temperatures and humidity levels in the ranges of 7–10 °C and 85–95%, respectively. Root-type vegetables, pumpkins, melons and tropical fruits require temperatures of 13–18 °C and relative humidity levels of 85–95%. Additionally, some crops produce ethylene, while others are sensitive to ethylene exposure, and hence they cannot be stored together to avoid detrimental effects, including yellowing, softening, browning, increased decay and abscission or loss of leaves [63]. The variation in optimal storage conditions for horticultural crops can pose a barrier to the storage of different crops in one storage space [62].

Table 6. Recommended storage conditions and properties of common fresh fruits and vegetables [44,63].

Commodities	Storage Temperature °C	Relative Humidity %	Controlled Atmosphere Conditions	Ethylene Production *	Ethylene Sensitivity	Recommended Storage Life
Cauliflower	0	95–98	O_2 (2–5%) + CO_2 (2–5%)	Very low	High	3–4 weeks
Broccoli	0	>95	O_2 (1–2%) + CO_2 (5–10%)	Very low	High	1–4 weeks
Celery	0	98–100	O_2 (2–4%) + CO_2 (3–5%)	Very low	Moderate	1–2 months
Artichoke (globe)	0	95–100	O_2 (2–3%) + CO_2 (3–5%)	Very low	Low	2–3 weeks
Lettuce	0	98–100	O_2 (2–5%) + CO_2 (0%)	Very low	High	2–3 weeks
Asparagus (green)	2.5	95–100	CO_2 (5–12%) in air	Very low	Moderate	2–3 weeks
Spinach	0	95–100	O_2 (5–10%) + CO_2 (5–10%)	Very low	High	1–2 weeks
Parsley	0	95–100	O_2 (5–10%) + CO_2 (5–10%)	Very low	High	1–2 months
Fennel	0–2	90–95	-	-	-	2–3 weeks
Radish (red)	0	95–100	O_2 (1–2%) + CO_2 (2–3%)	Very low	Low	1–2 months
Peas (snow; snap; sugar in pods)	0	90–98	O_2 (2–3%) + CO_2 (2–3%)	Very low	Moderate	1–2 weeks
Squash (zucchini)	7–10	95	O_2 (3–5%) + CO_2 (5–10%)	Low	Moderate	1–2 weeks
Cucumber	10–12	95%	O_2 (3–5%) + CO_2 (<5%)	Low	High	10–14 days
Beans: snap; green	4–7	95	O_2 (2–3%) + CO_2 (4–7%)	Low	Moderate	7–10 days
Cabbage (round and Chinese types)	0	95–100	O_2 (3–5%) + CO_2 (2.5–6%)	Very low	Moderate to high	2–6 months
Tomato, mature–green	10–13	90–95	O_2 (3–5%) + CO_2 (2–3%)	Very low	High	2–5 weeks
Tomato, firm–ripe	8–10	85–90	O_2 (3–5%) + CO_2 (3–5%)	High	Low	1–3 weeks
Banana, mature–green	13–14	90–95	O_2 (2–5%) + CO_2 (2–5%)	Moderate	High	1–4 weeks
Avocado; Hass	3–7	85–90	O_2 (2–5%) + CO_2 (3–10%)	High	High	2–4 weeks
Grape (table type)	−0.5–0	90–95	O_2 (2–5%) + CO_2 (1–3%)	Very low	Low	1–6 months

* Ethylene production rates (μL/kg-h): very low (<0.1 at 20 °C), low (0.1–1.0), moderate (1.0–10.0), high (10–100), very high (>100).

Consumers' demands for fresh fruits and vegetables drive the need for cold storage in value chains due to the fact that in their state of freshness, the nutritional and sensory potentials are high and provide a wide range of processing opportunities for the consumer. Moreover, cold room storage can reduce and/or prevent postharvest losses of fruit and vegetables caused by dust, insect, microbial, sunlight and biological degradation and hence increase the availability of fresh and nutritious food for consumers [35]. Furthermore, socioeconomic factors, such as poor marketing systems, transportation facilities, market information and government regulations, should be addressed to achieve the whole purpose of cold chain.

7. Conclusions

Overcoming the issue of postharvest loss of fruits and vegetables through cold storage requires considerable efforts in terms of energy and capital expenditure and skilled personnel. However, the sustainability and environmental impacts of introducing new cold chain technologies should be taken into consideration. The use of off-grid and cost-effective green energy sources, such as solar-powered cold storage technologies, could be a suitable way forward in expanding cold chain availability in developing countries. Appropriate and wide application of such technologies will facilitate access to fresh and nutritious fruit and vegetable production to rural farmers and ultimately improve food and nutrition security and farmers' livelihoods. It will lead to availability of healthy fruit and vegetables to the wider population and drive economic growth and positive health outcomes.

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